PRC and JPS-DNP joint symposium at 2021 fall JPS meeting

Hypernuclear Physics at Jefferson Laboratory

Kyoto University, Japan

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Sep 17, 2021

GRADUATE SCHOOL OF SCIENCE
FACULTY OF SCIENCE
KYOTO UNIVERSITY

科研費 KAKENHI

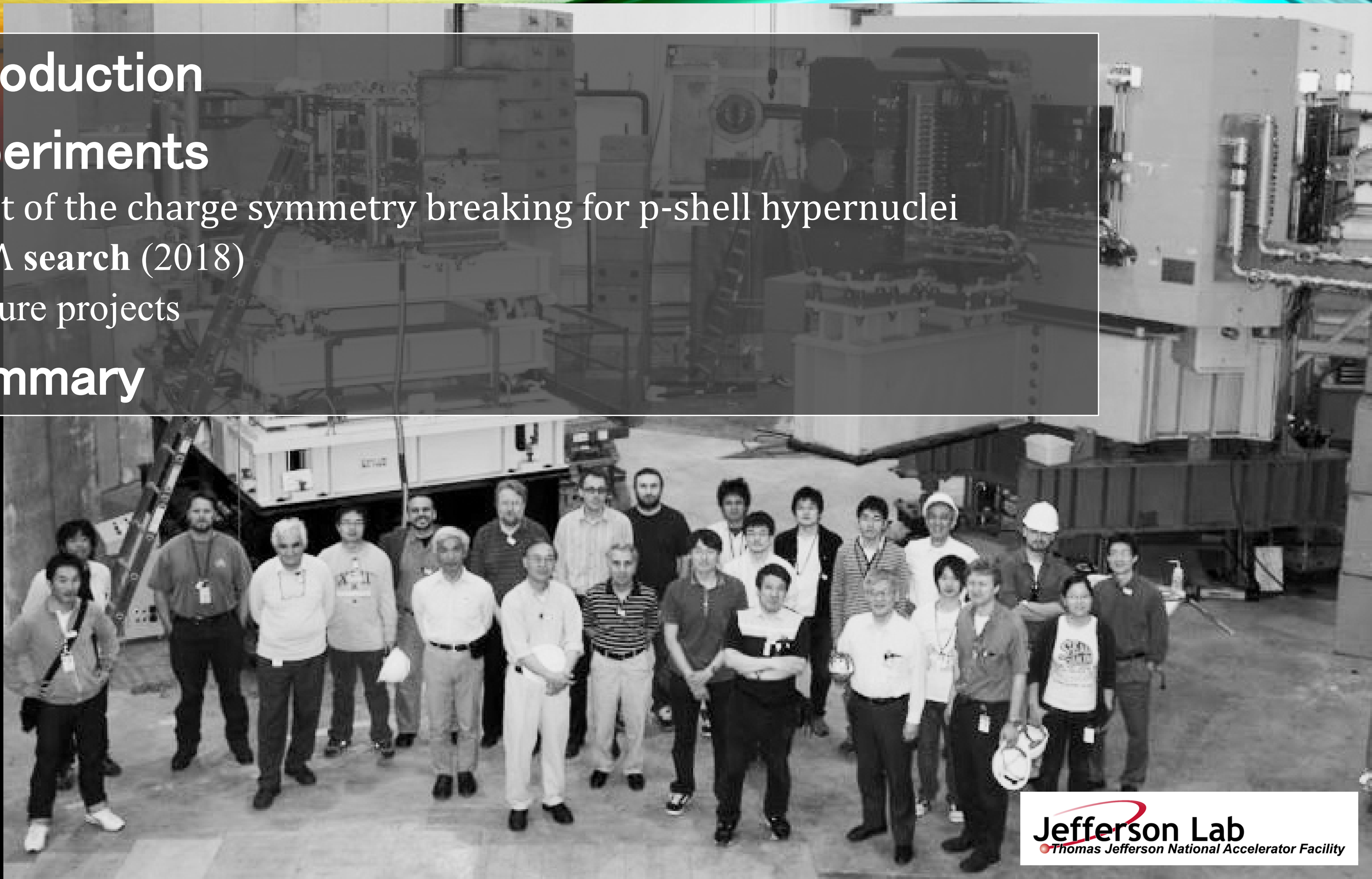
SPIRITS
SUPPORTING PROGRAM FOR INTERACTION-BASED INITIATIVE TEAM STUDIES

1. Introduction

2. Experiments

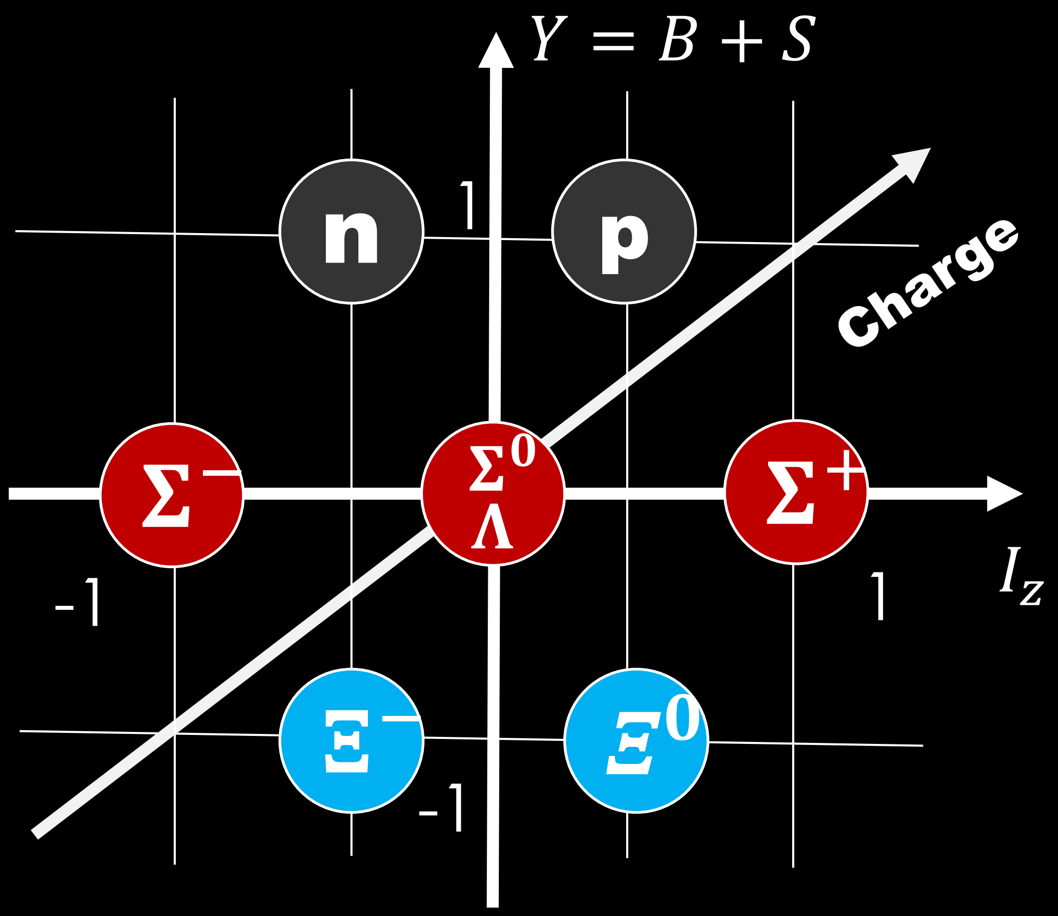
- Test of the charge symmetry breaking for p-shell hypernuclei
- $nn\Lambda$ **search** (2018)
- Future projects

3. Summary



Jefferson Lab
Thomas Jefferson National Accelerator Facility

STUDY ON BARYON INTERACTION (BB INT.)



Baryon Octet $J^\pi = \frac{1}{2}^+$

<u>Nuclear Sector (NN)</u>

- Rich data of scattering experiment
- Nuclear data > 3000

<u>Strangeness Sector (ΛN, ΣN, ΞN etc.)</u>

- Scarce data of scattering experiment
- Hypernuclear data ~ only 40 !!

Available facilities for HN experiments:

- ◆ $S = -1$: CERN, RHIC, GSI, J-PARC, MAMI, **JLab**
- ◆ $S = -2$: J-PARC, FAIR

HOW TO INVESTIGAE THE BB INTERACTION

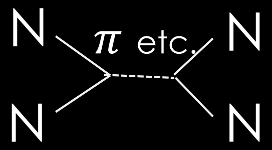
Method A

Data

- Scattering experiment
- (hyper)nuclear spectroscopy
- Phemtoscopy (ALICE, PRL123, 112002 (2019))

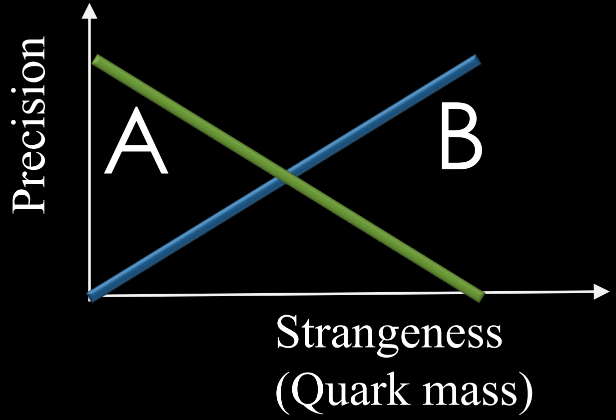
Phenomenological Theories

- Meson exchange model
- Effective field theory
- Quark cluster model etc.



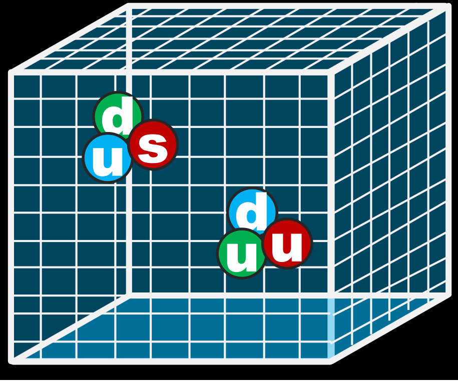
H. Yukawa (Kyoto Univ.)
Novel Prize 1949

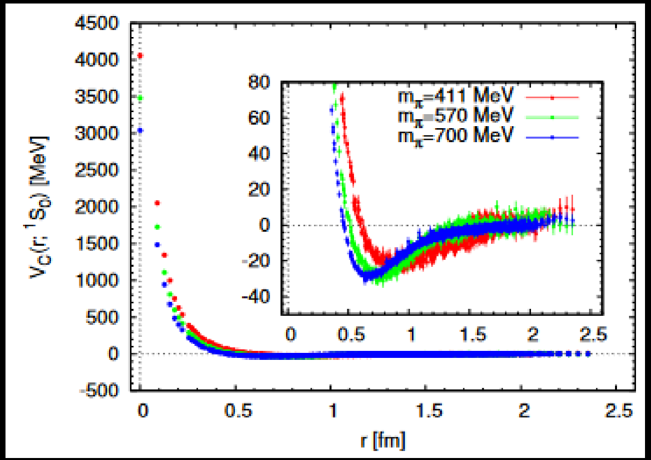
Complementary



Method B

Lattice QCD
(First principle calc.)

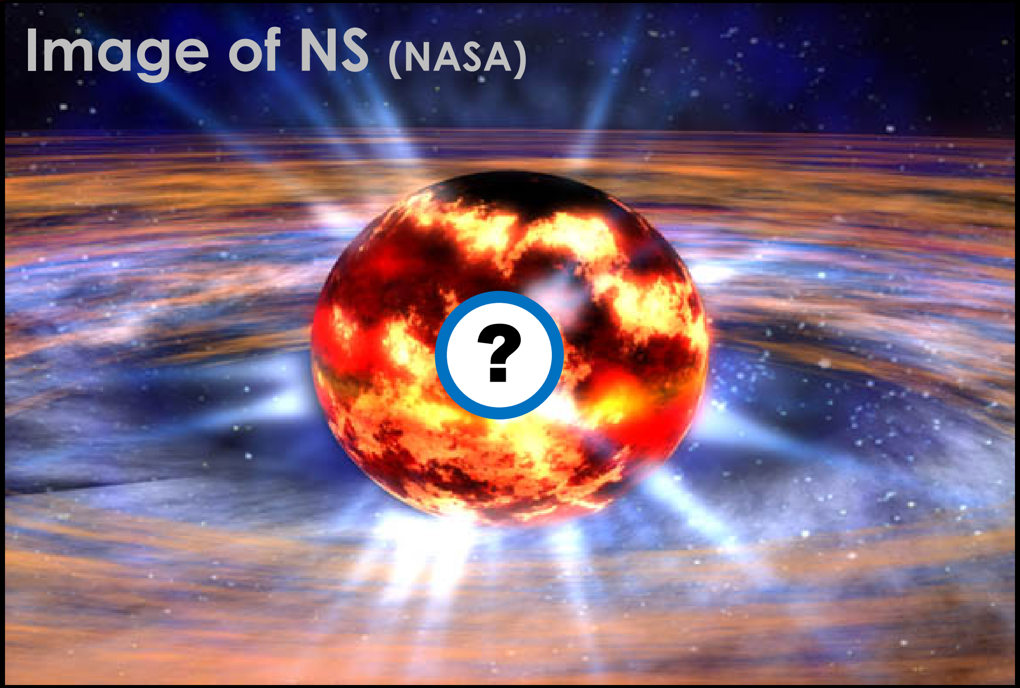




arXiv:2003.10730v2 [hep-lat] 12 Jul 2020

BB interaction (Strong force)

HYPERONS IN NATURE



Astronomical observation

- space observation
- gravitational wave

What's inside ?

- ☐ Strange Hadrons?
- ☐ Quark matter?
- ☐ Meson condensate?

<u>Hyperons make a NS softer</u>

→$\geq 2M_{\odot}$ is hard to support by only 2BF

→Multi body repulsive forces may play a role

More precise studies on the strange BB/BBB interactions are needed

Typical options for hypernuclear measurement

Production measurement

Missing mass spectroscopy

- ✓ (π^+, K^+) @J-PARC
- ✓ (K^-, π^-) @J-PARC
- ✓ $(e, e'K^+)$ @JLab

⇨ **<u>Mass</u>**, production mechanism

Better precision!

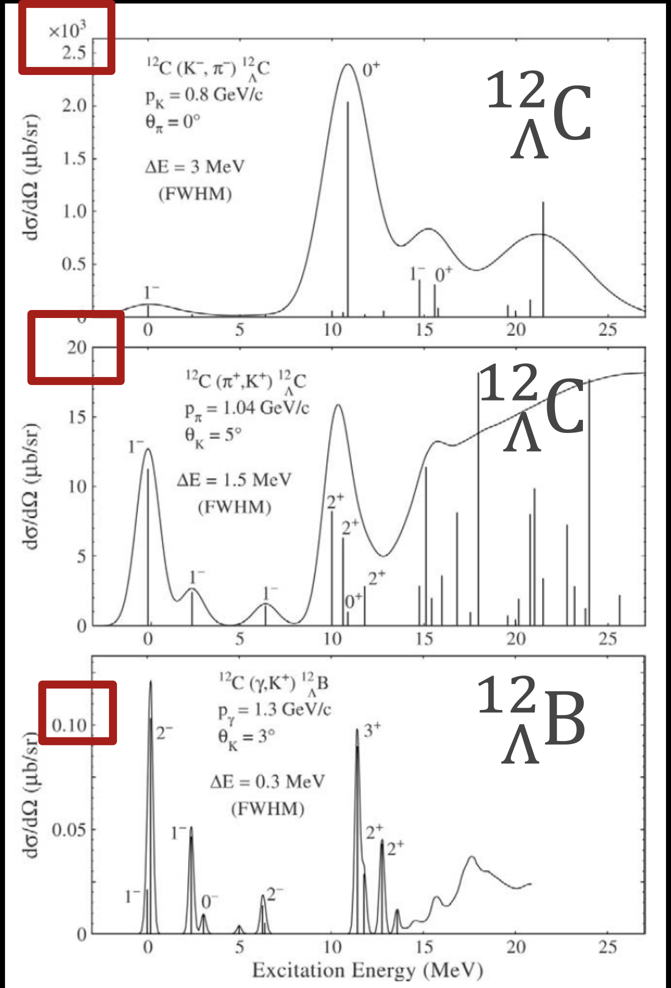
Decay particle measurements

- Emulsion @J-PARC
- Invariant mass spectroscopy @GSI
- γ-ray spectroscopy @ J-PARC
- Decay π spectroscopy @MAMI
- (femtoscopy @CERN)

⇨ Mass, Lifetime, decay mechanism

DRAWBACK AND ADVANTAGE

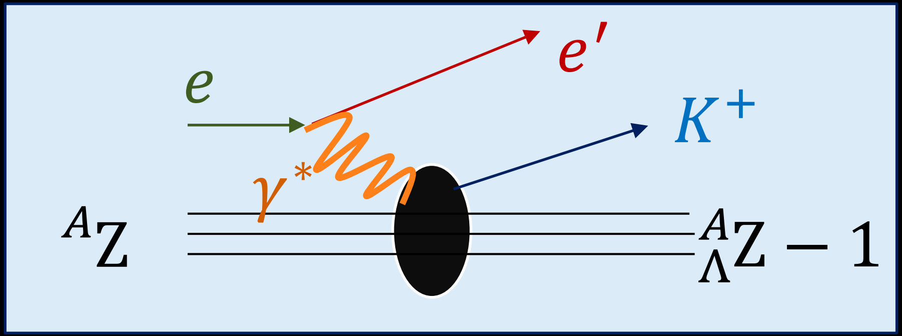
Hypernuclei from ^{12}C



(K^-,π^-)

(π^+,K^+)

$(e,e'K^+)$

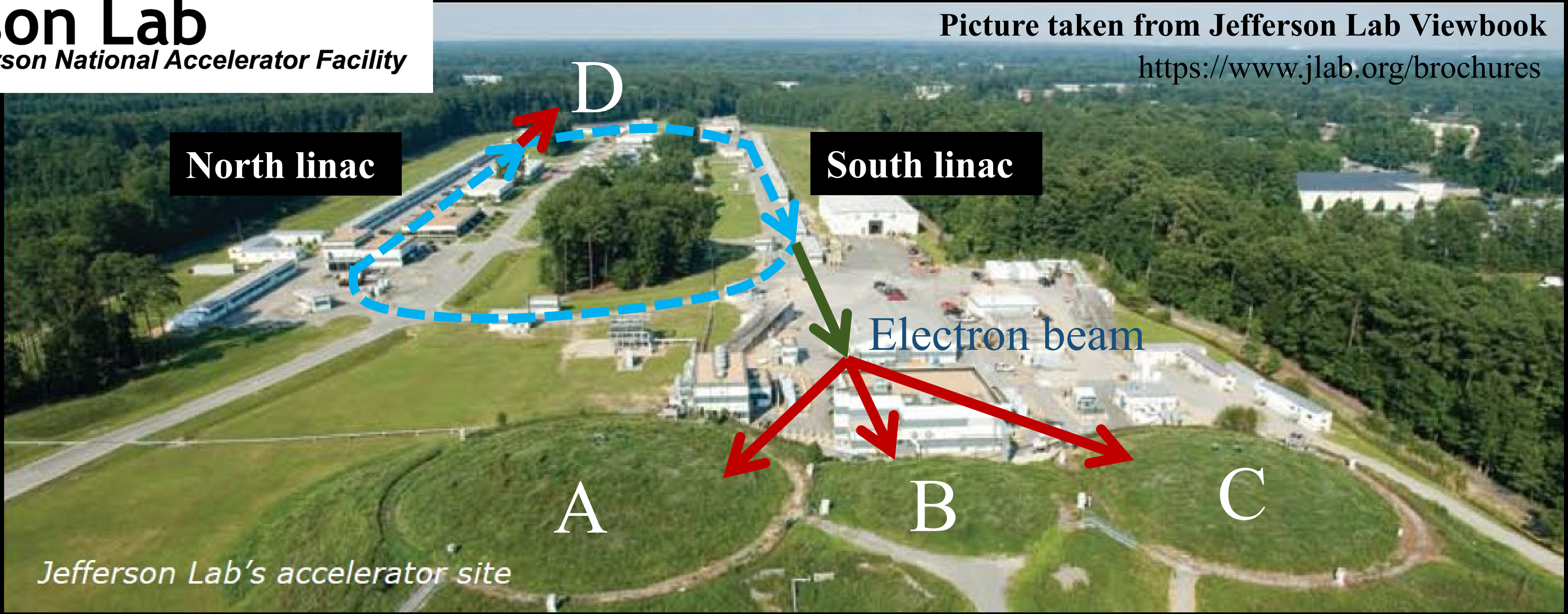


- High resolution (< 1 MeV) ◎
- Production of mirror nuclei ◎
- Large spin flip amplitude △
- Very small cross section ×
- Huge EM backgrounds ×
- e' and K⁺ coincidence ×

➡ Good but difficult!

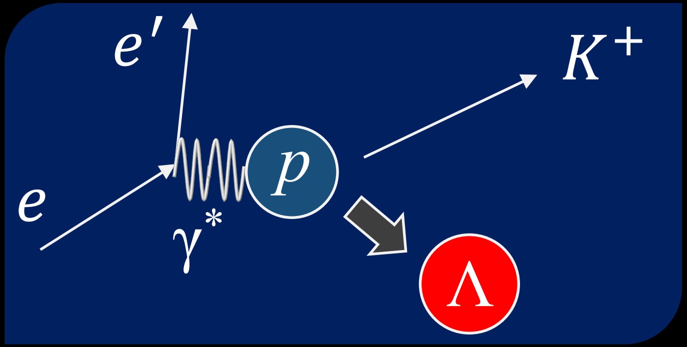
TG et al., Nucl. Instrum Methods. Phys. A 900, 69—83 (2018)

CEBAF AT JEFFERSON LAB

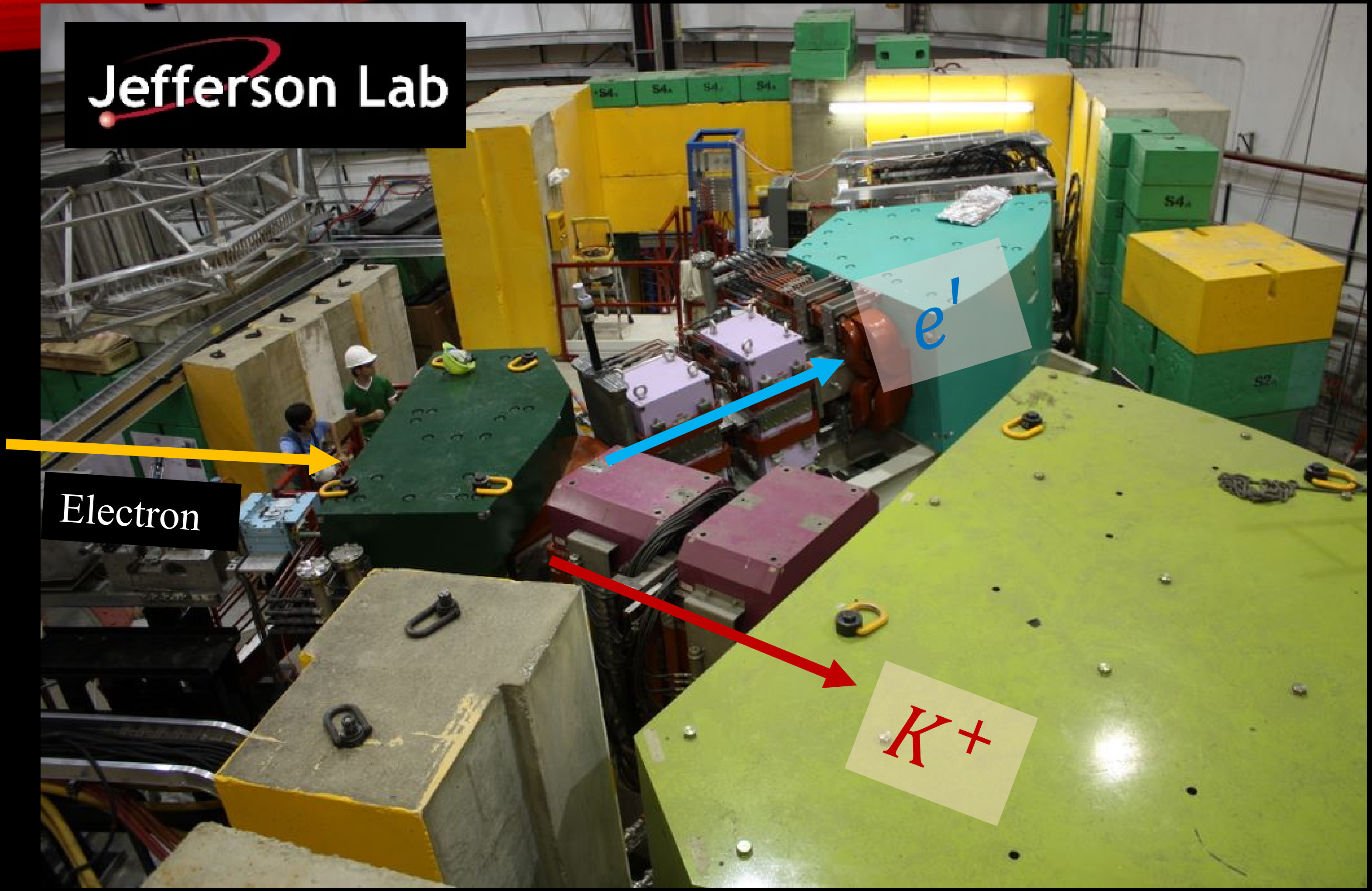


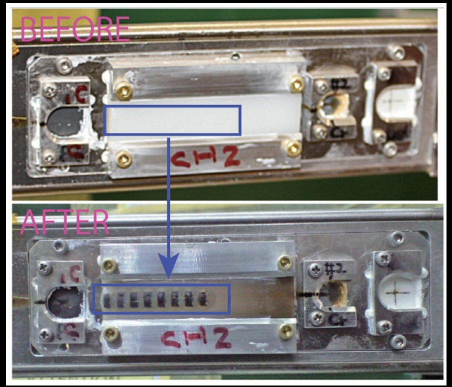
Continuous electron beam facility (CEBAF)

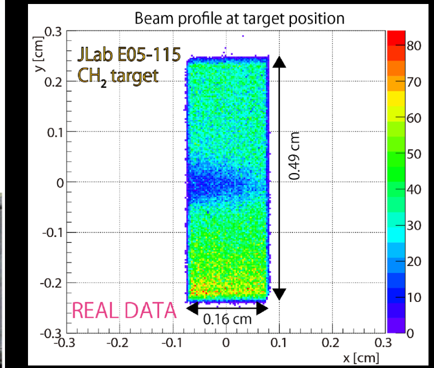
- ✓ 12 GeV at maximum
- ✓ 100 μA (> 600 THz)
- ✓ 2 or 4-ns interval bunches
- ✓ Emittance of 2 μm·mrad
- ✓ Energy spread ($^{\Delta E}/_{E} < 5 \times 10^{-5}$ rms)

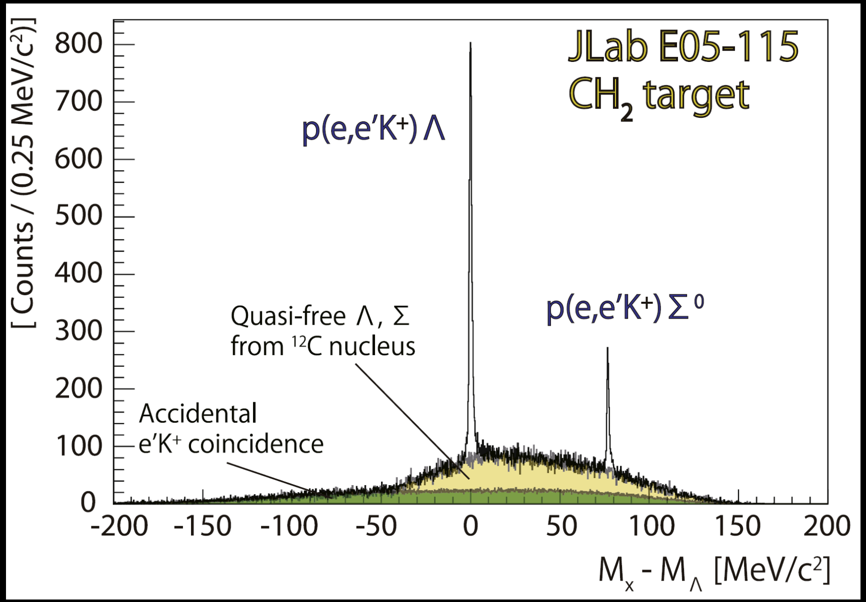


Experimental setup



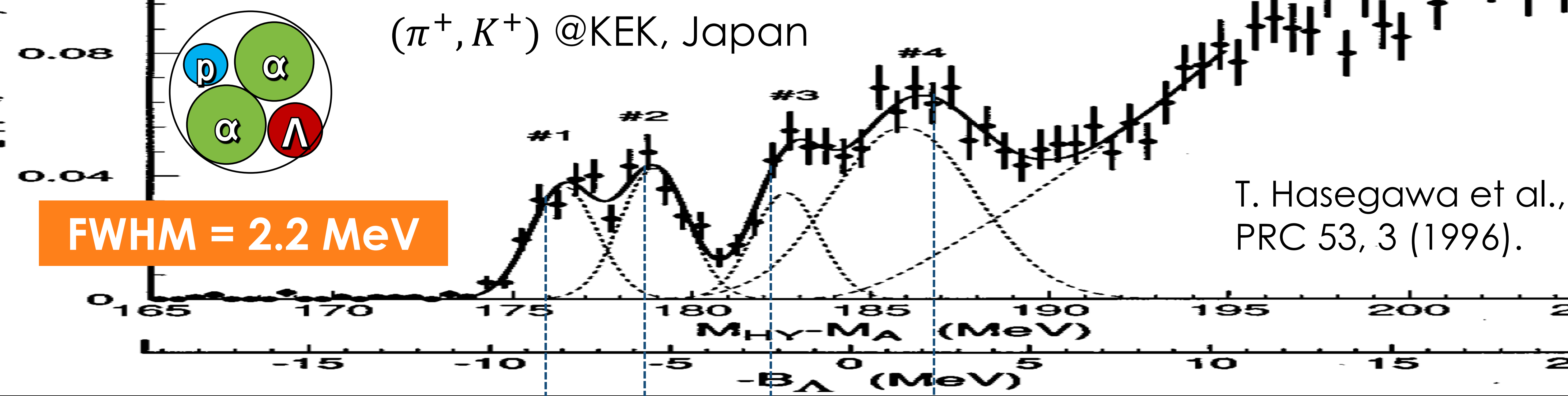






✓ High resolution
✓ High accuracy

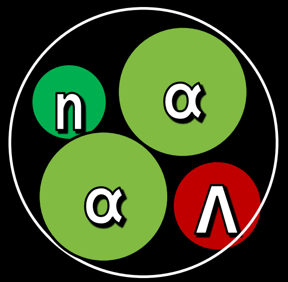
- TG et al., Nucl. Instrum Methods. Phys. A 729, 816—824 (2013)
- Y. Fujii et al., Nucl. Instrum Methods. Phys. A 795, 351—363 (2015)



FWHM = 2.2 MeV

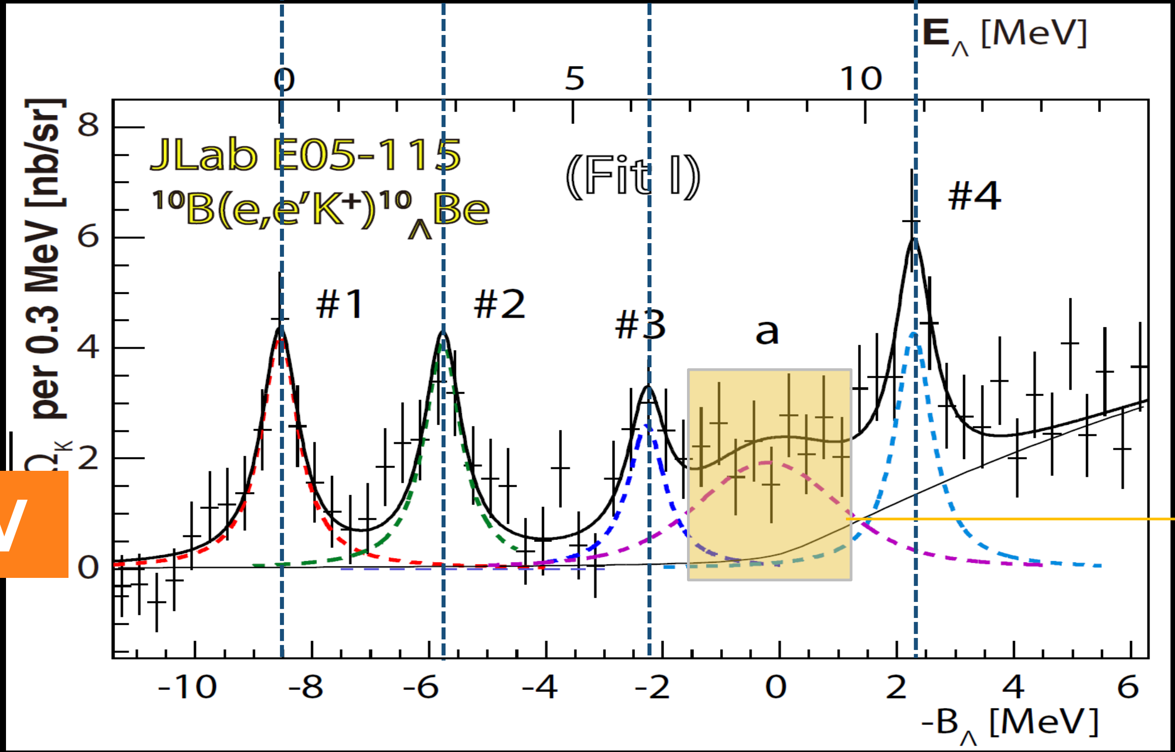
T. Hasegawa et al.,
PRC 53, 3 (1996).

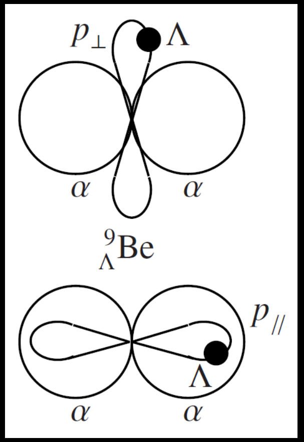
$^{10}_{\Lambda}\mathrm{Be}$



FWHM = 0.8 MeV

TG et al.,
PRC 93, 034314 (2016).





A. Umeya *et al., J. Phys.: Conf. Ser.* **1643** 012110 (2020).

CHARGE SYMMETRY BREAKING (CSB)

*1) T. O. Yamamoto *et al.* (J-PARC E13 Collaboration), Phys. Rev. Lett. 115, 222501 (2015)
*2) A. Esser *et al.* (A1 Collaboration), Phys. Rev. Lett. 114, 232501 (2015).

^{3}He **^{3}H**

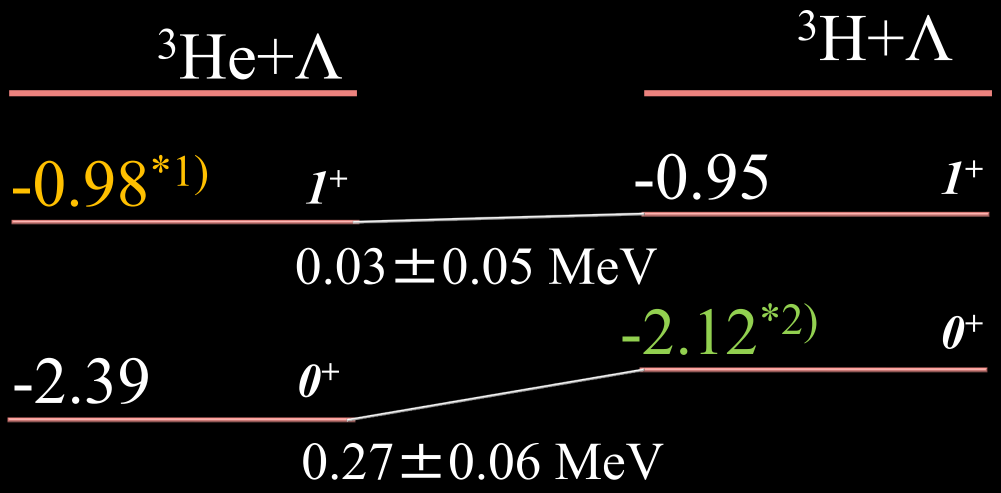
$\Delta B = 0.76384\ (26)^{*1)}$ MeV
$\Delta B_{\text{Coulomb}} = 0.683^{*2)}$ MeV

➡ ***0.081 MeV***

*1) J.H.E.Mattauch *et al., Nucl. Pys.* **67**, 1 (1965).
*2) R.A.Brandenburg, S.A.Coon *et al., NPA***294,** 305 (1978).

$^{4}_{\Lambda}$He

$^{4}_{\Lambda}$H

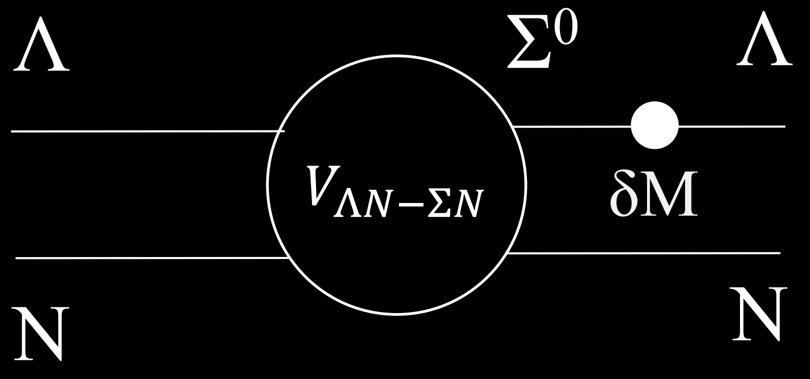


➡ ***≈0.4 MeV w/ correction***

- ☐ Five times larger effect
- ☐ Spin dependent

ΛN-ΣN COUPLING

A. Gal, Phys. Lett. B 744, 352 (2015)



$$\langle N\Lambda|V_{CSB}|N\Lambda\rangle = -0.0297\tau_{Nz}\frac{1}{\sqrt{3}}\langle N\Sigma|V_{CS}|N\Lambda\rangle$$

ΔE(0+) = 266 keV
ΔE(1+) = 39 keV

ΛN-ΣN COUPLING

A. Gal, Phys. Lett. B 744, 352 (2015)

What about other systems such as the p-shell region?

$$\ldots B|N\Lambda\rangle = -0.0297\tau_{Nz}\frac{1}{\sqrt{3}}\langle N\Sigma|V_{CS}|N\Lambda\rangle$$

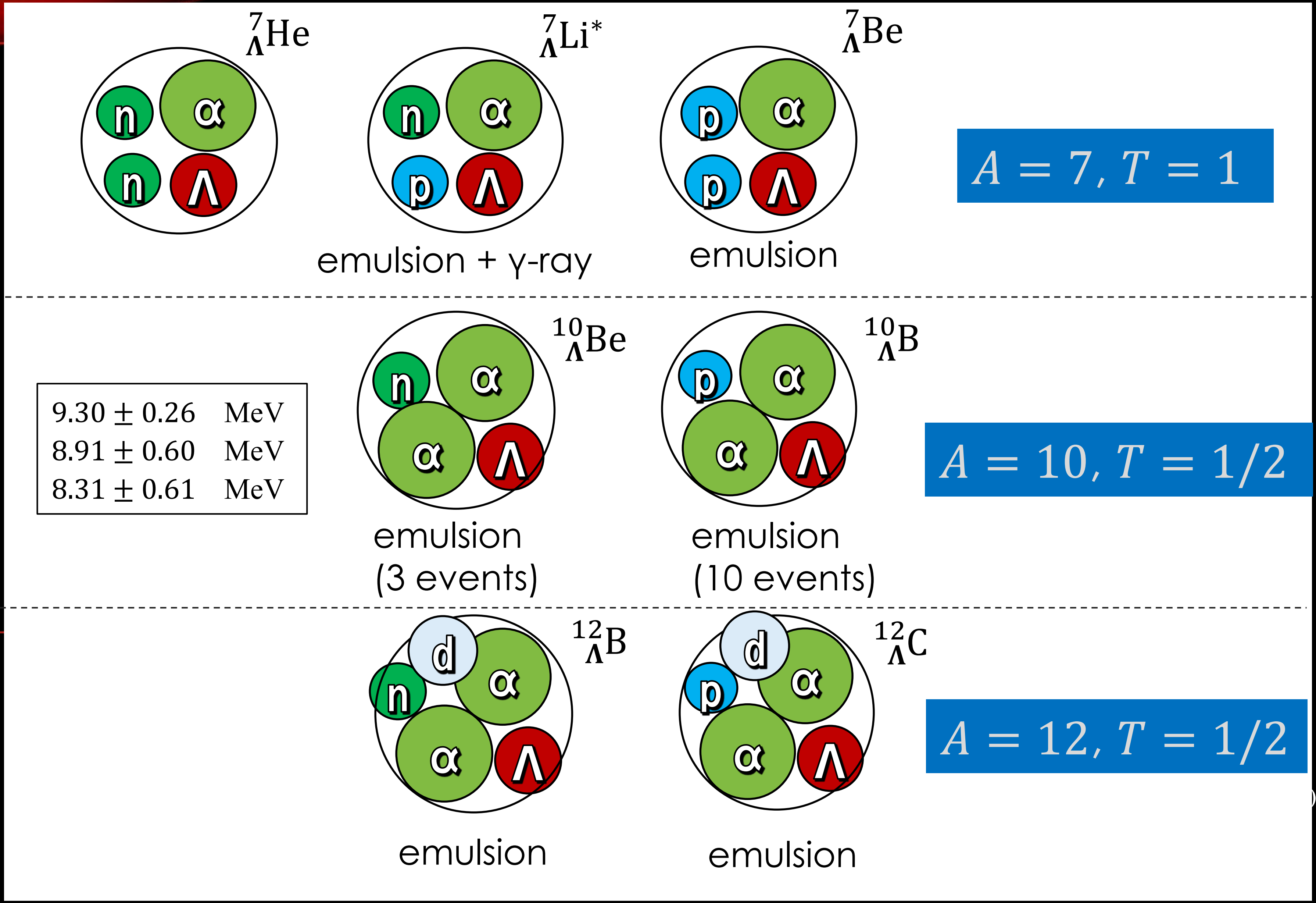
p-shell → matrix elements are **smaller** compared to those for s-shell by a factor of 2

(The matrix elements are determined to reproduce γ-ray transition energies;
D.J. Millener, Nucl. Phys. A 881, 298—309 (2012))

Charge symmetry breaking (CSB) in the p-Shell hypernuclei

A. Gal et al., J. Phys.: Conf. Ser. 966 012006 (2018)

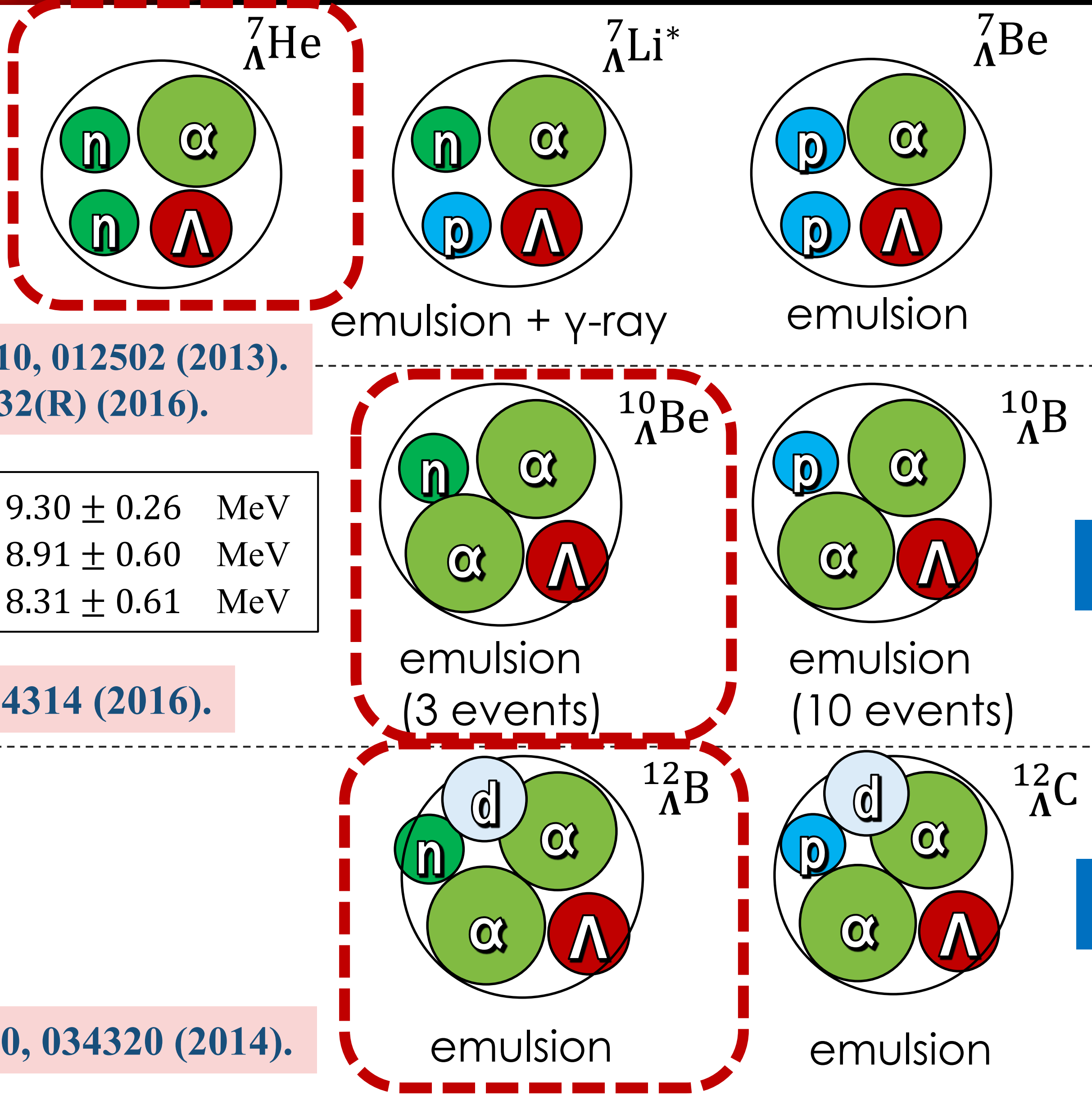
Expected difference



15—30 keV

136 keV

Charge symmetry breaking (CSB) in the p-Shell hypernuclei



$A = 7, T = 1$

S.N.Nakamura, PRL 110, 012502 (2013).
TG et al., PRC 94, 02132(R) (2016).

$^{9}_{\Lambda}$Li vs. $^{9}_{\Lambda}$B

TG et al., PRC 103, L041301 (2021)

9.30 ± 0.26	MeV
8.91 ± 0.60	MeV
8.31 ± 0.61	MeV

$A = 10, T = 1/2$

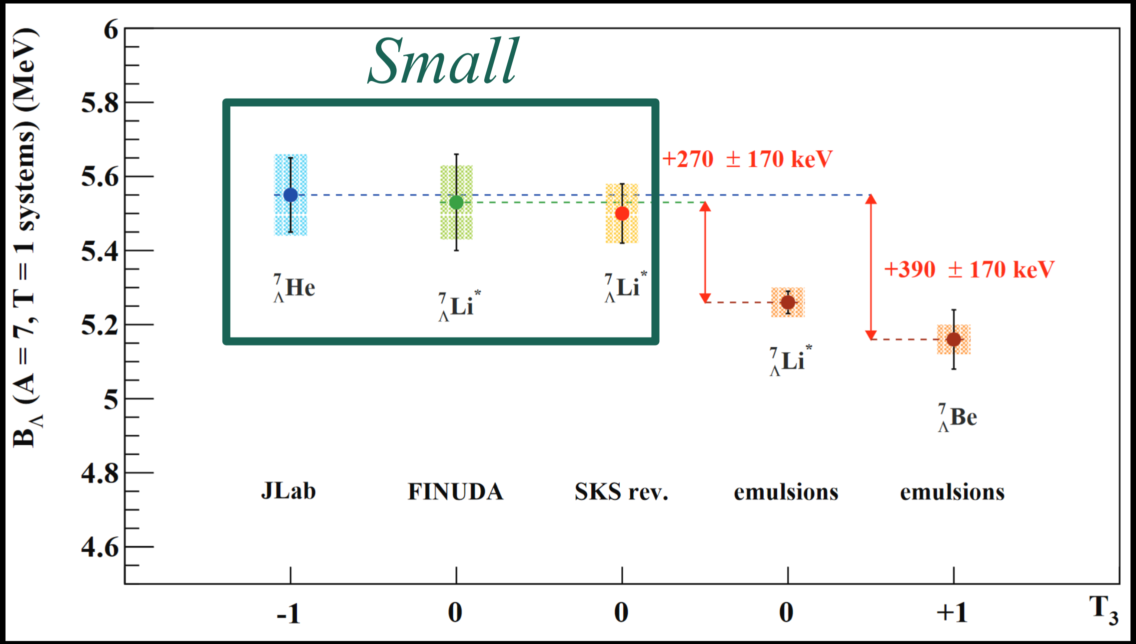
TG et al., PRC 93, 034314 (2016).

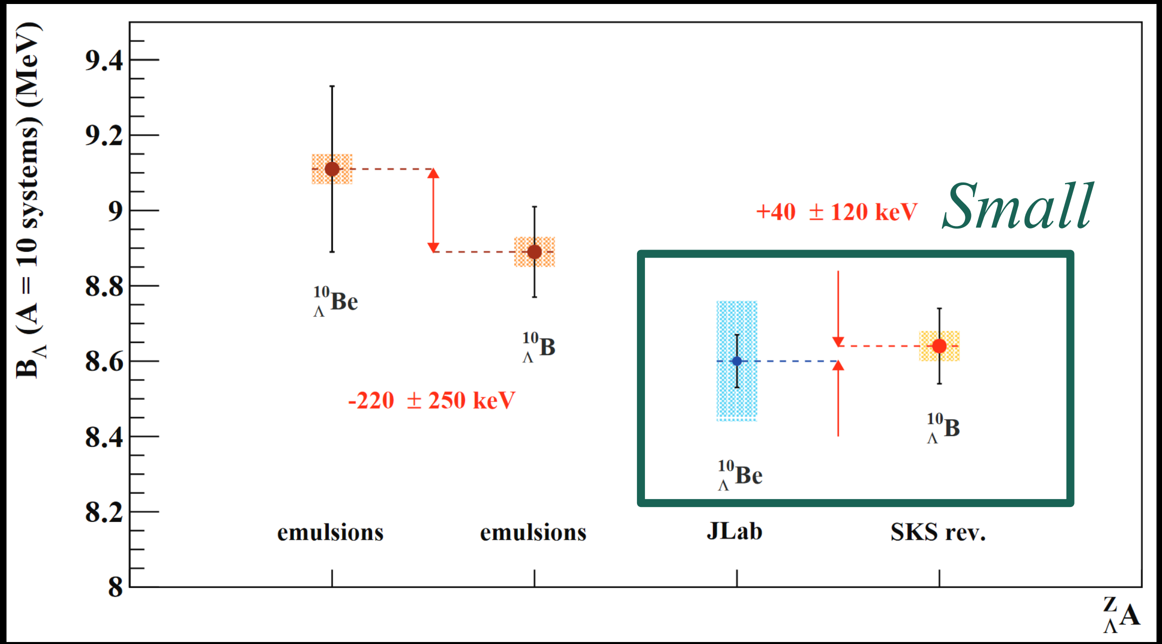
$A = 12, T = 1/2$

L. Tang et al., PRC 90, 034320 (2014).

RESULTS

E. Botta, AIP Conference Proceedings 2130, 030003 (2019)



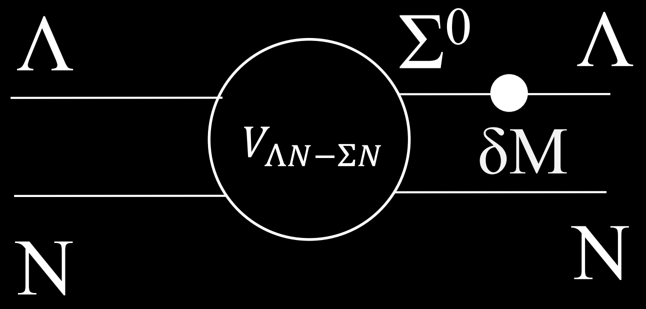


- CSB seems to be small in p-shell when counting experiments' data are used
- Double check is awaited for emulsion data → J-PARC E07 (data were taken)

BASIC INFORMATION FOR THE ΛN CSB STUDY: ${}^4_\Lambda\mathrm{He} - {}^4_\Lambda\mathrm{H}$

Explicit inclusion of Σ

A. Gal, Phys. Lett. B 744, 352 (2015)



$$\langle N\Lambda|V_{CSB}|N\Lambda\rangle = -0.0297\tau_{Nz}\frac{1}{\sqrt{3}}\langle N\Sigma|V_{CS}|N\Lambda\rangle$$

Phenomenological potential

E. Hiyama et al., Phys. Rev. C **80**, 054321 (2009).
M. Isaka et al., Phys. Rev. C 101, 024301 (2020).

$$V^{\rm CSB}_{\Lambda N}(r) = -\frac{\tau_z}{2}\left[\frac{1+P_r}{2}\left(v_0^{\rm even,CSB} + \sigma_\Lambda\cdot\sigma_N v^{\rm even,CSB}_{\sigma_\Lambda\cdot\sigma_N}\right)e^{-\beta_{\rm even}r^2} + \frac{1-P_r}{2}\left(v_0^{\rm odd,CSB} + \sigma_\Lambda\cdot\sigma_N v^{\rm odd,CSB}_{\sigma_\Lambda\cdot\sigma_N}\right)e^{-\beta_{\rm odd}r^2}\right]$$

Basic Input

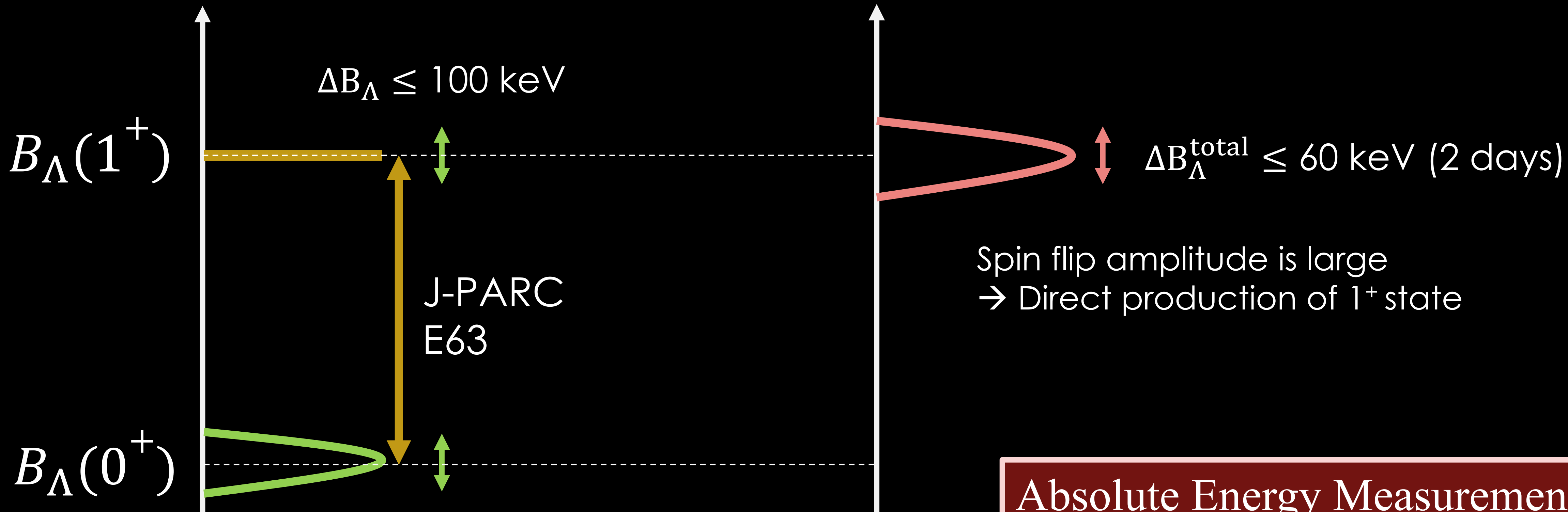
JLab → $B_\Lambda({}^4_\Lambda\mathrm{H};\ 1^+)$

A=4 → **CSB interaction** →

- A=5 — HKS, PRL 110, 012502 (2013)
- A=7 — HKS, PRC 94, 021302(R) (2016)
- A=9 — Hall A, PRC 91,034308 (2015)
- HKS, PRC103, L041301 (2021)
- A=10 — HKS, PRC 93, 034314 (2016)
- … — HKS, PRC 90, 034320 (2014) …

HOW WE CONFIRM THE $B_\Lambda({}^4_\Lambda\mathrm{H};\ 1^+)$

Conventional way | JLab E12-19-002



- Emulsion: $\mathbf{2.08 \pm 0.06 \pm 0.04}$ **MeV** (1)
- MAMI: $\mathbf{2.12 \pm 0.01 \pm 0.09}$ **MeV** (2)

Absolute Energy Measurement:
- Very unique (direct meas.)
- Complementary with other data

(1) NPB 52, 1-30 (1973)
(2) PRL 114, 232501 (2015)

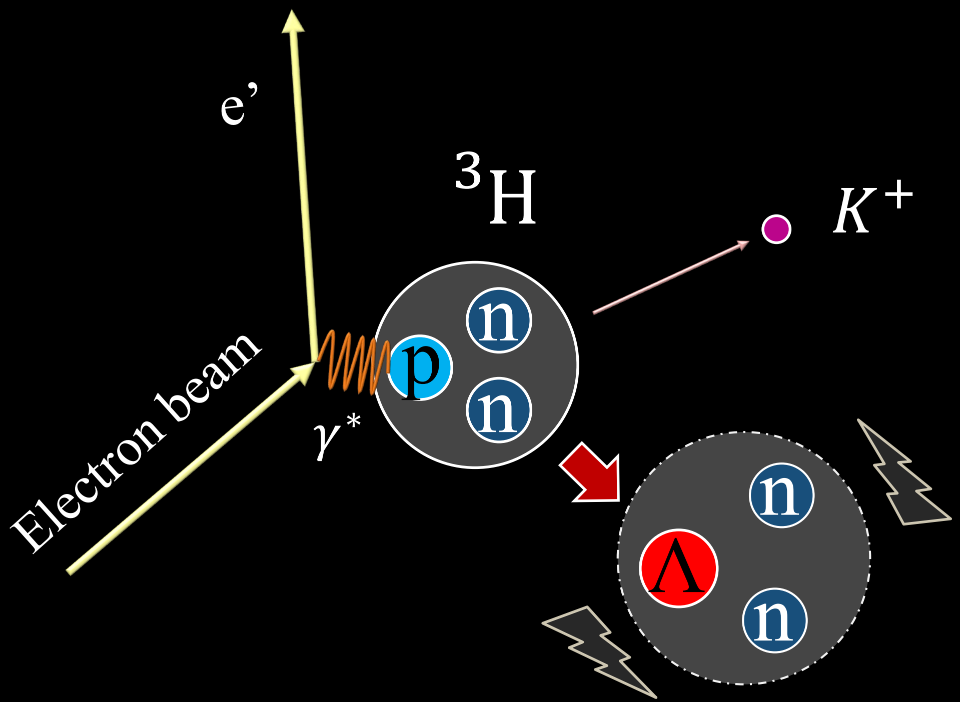
nnΛ search experiment at JLab (E12-17-003)

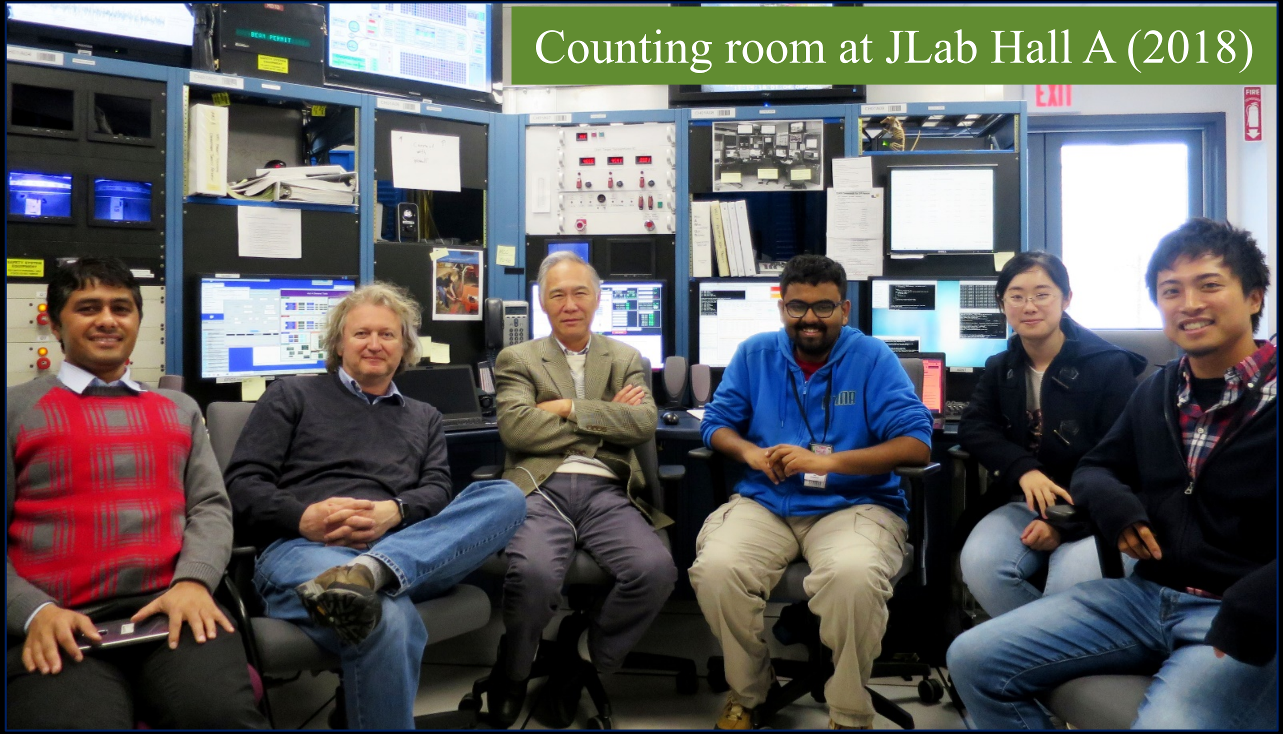
C. Rappold et al. (HypHI Collaboration), Phys. Rev. C 88, 041001(R) (2013).

bound nnΛ?

$^{3}H(e, e'K^{+})nn\Lambda$ with HRSs

E12-17-003 (Oct 30—Nov 25, 2018)



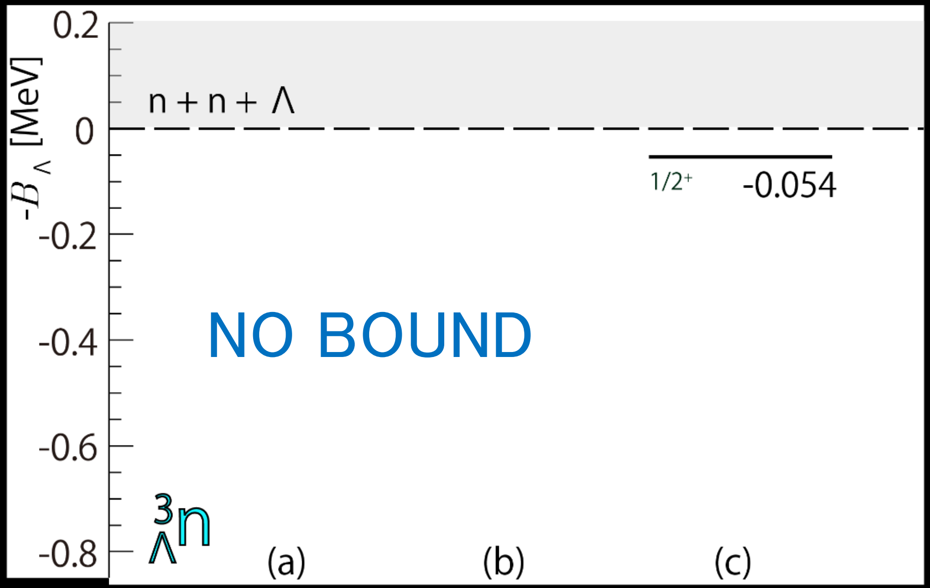


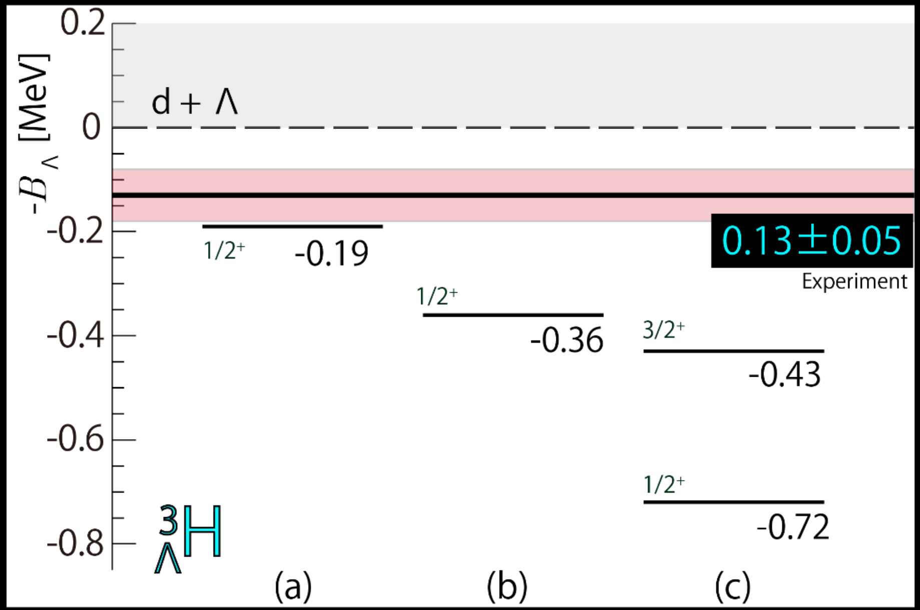
Missing mass measurement has sensitivity to both bound and resonant states

CAN THE $NN\Lambda$ BE BOUND?

E. Hiyama, S. Ohnishi, B.F. Gibson, and Th. A. Rijken, Physical Review C 89, 061302(R) (2014).

AV8 ***NN*** + NSC97f ***YN*** potentials

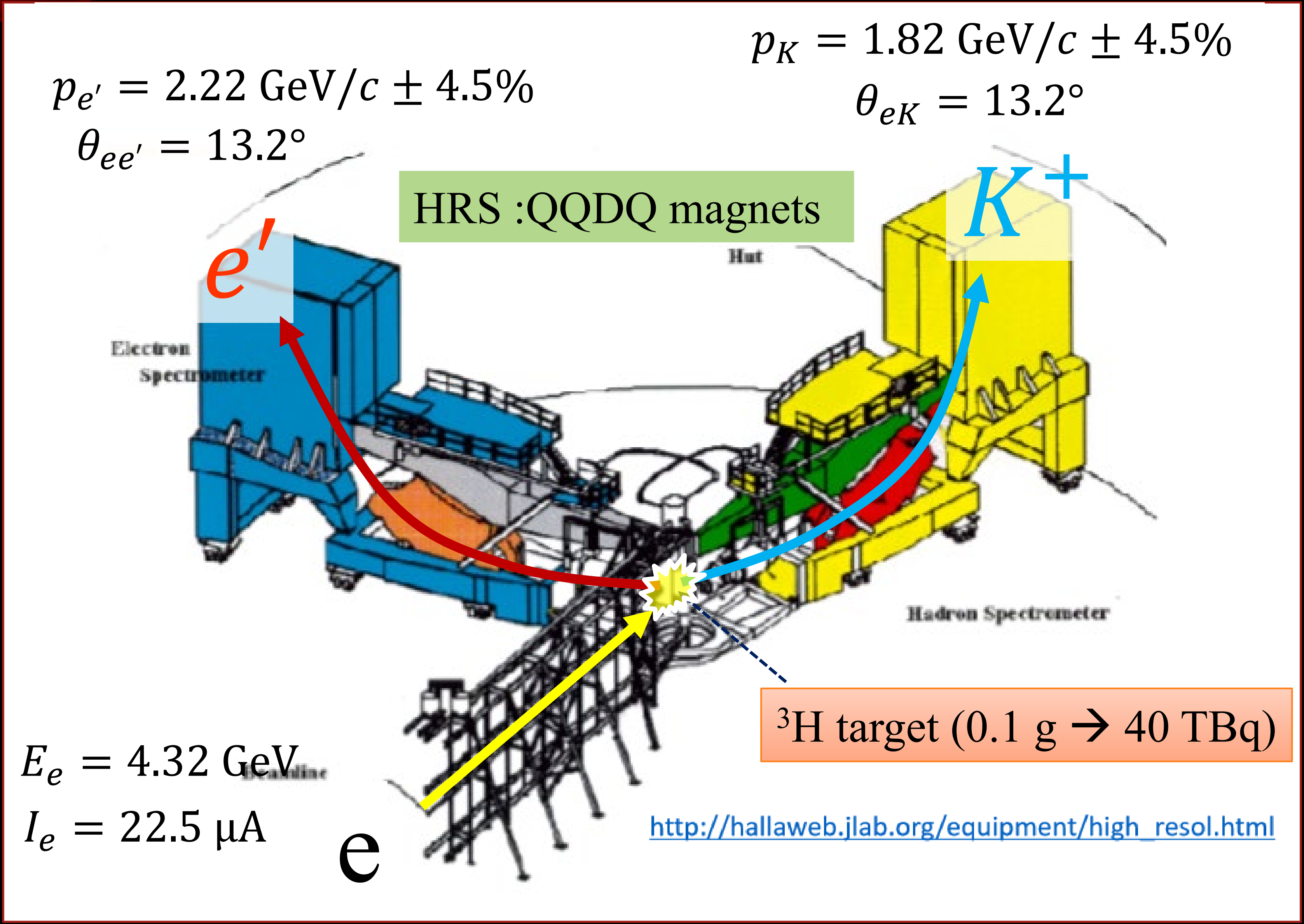




(a)	${}^{3}V^{T}_{\Lambda N-\Sigma N} \times 1.0$
(b)	${}^{3}V^{T}_{\Lambda N-\Sigma N} \times 1.1$
(c)	${}^{3}V^{T}_{\Lambda N-\Sigma N} \times 1.2$

Tensor component of the ΛN-ΣN coupling was varied.
→ No solution was found to make the *nn*Λ bound maintaining the consistency with the ${}^{3}_{\Lambda}$H (${}^{4}_{\Lambda}$H, ${}^{4}_{\Lambda}$He) data.

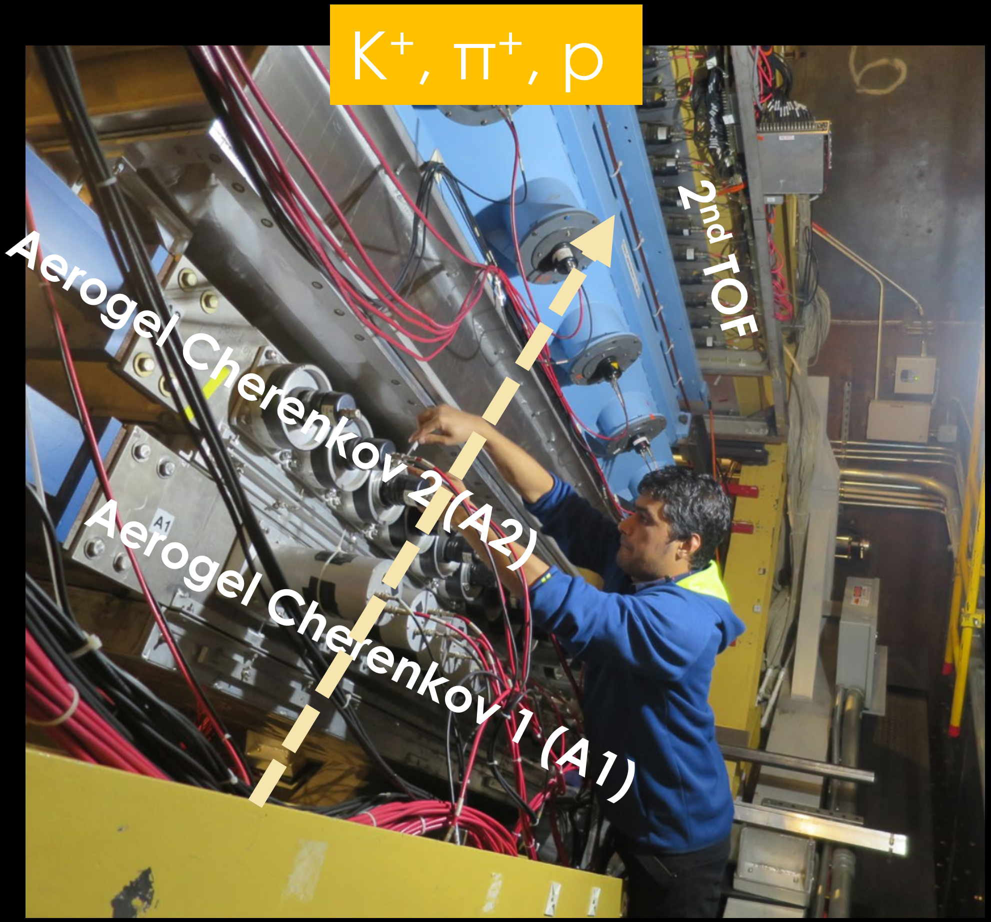
EXPERIMENTAL SETUP (JLAB E12-17-003)

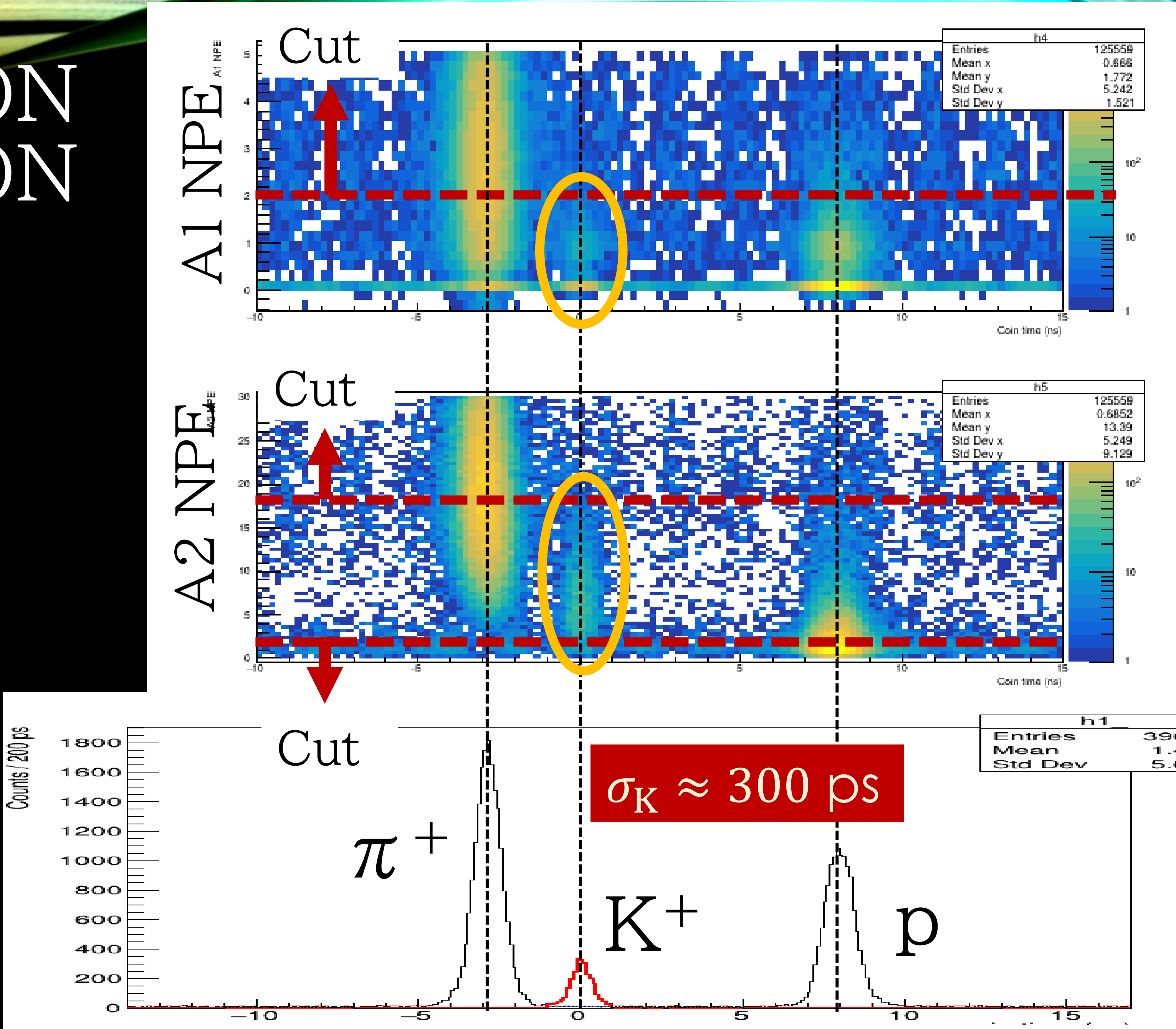


LHRS


RHRS
JLab Hall A (Apr 2019)
KYOTO UNIVERSITY
KYOTO JAPAN
FOUNDED 1897
HAMPTON UNIVERSITY
150 years
40 years
CELEBRATING A LEGACY AND A LEGEND OF EXCELLENCE
Jefferson Lab
Thomas Jefferson National Accelerator Facility

KAON IDENTIFICATION

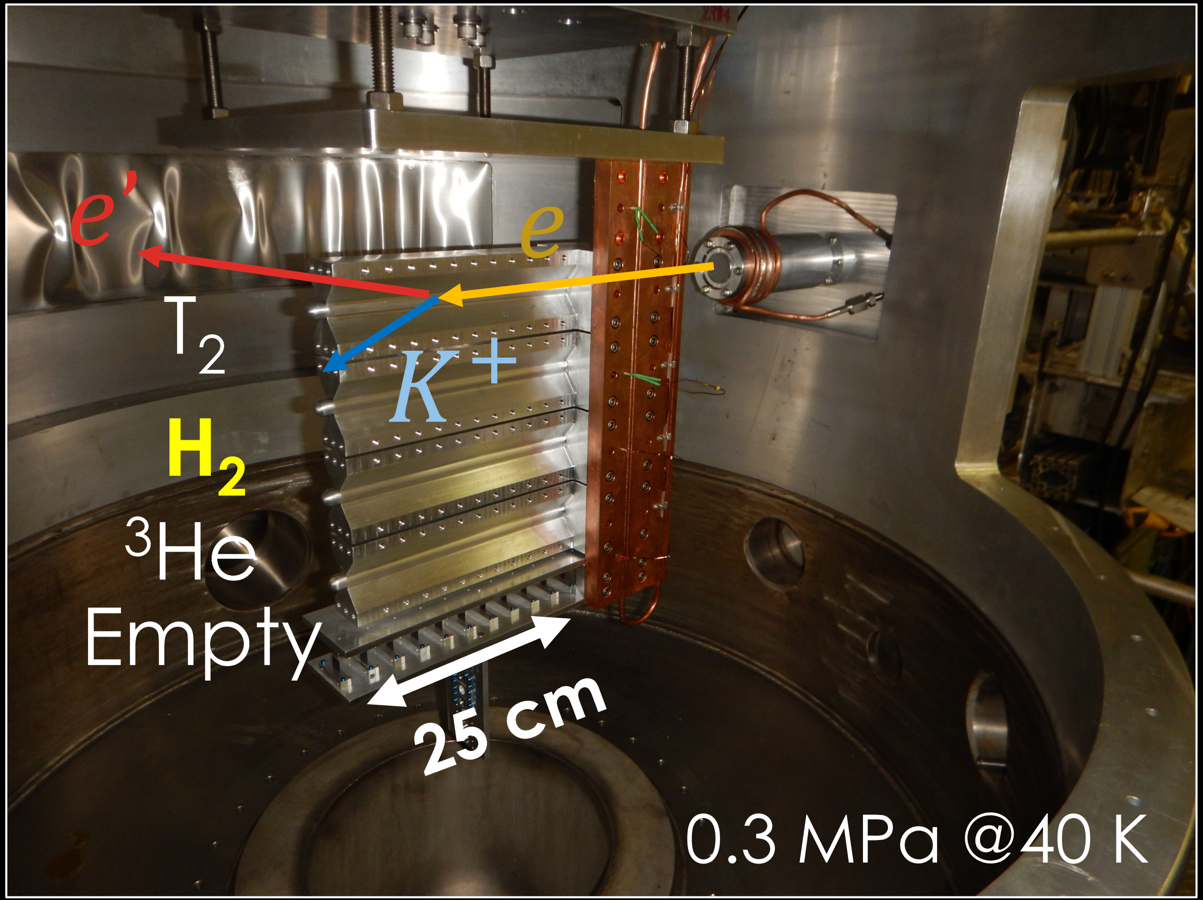




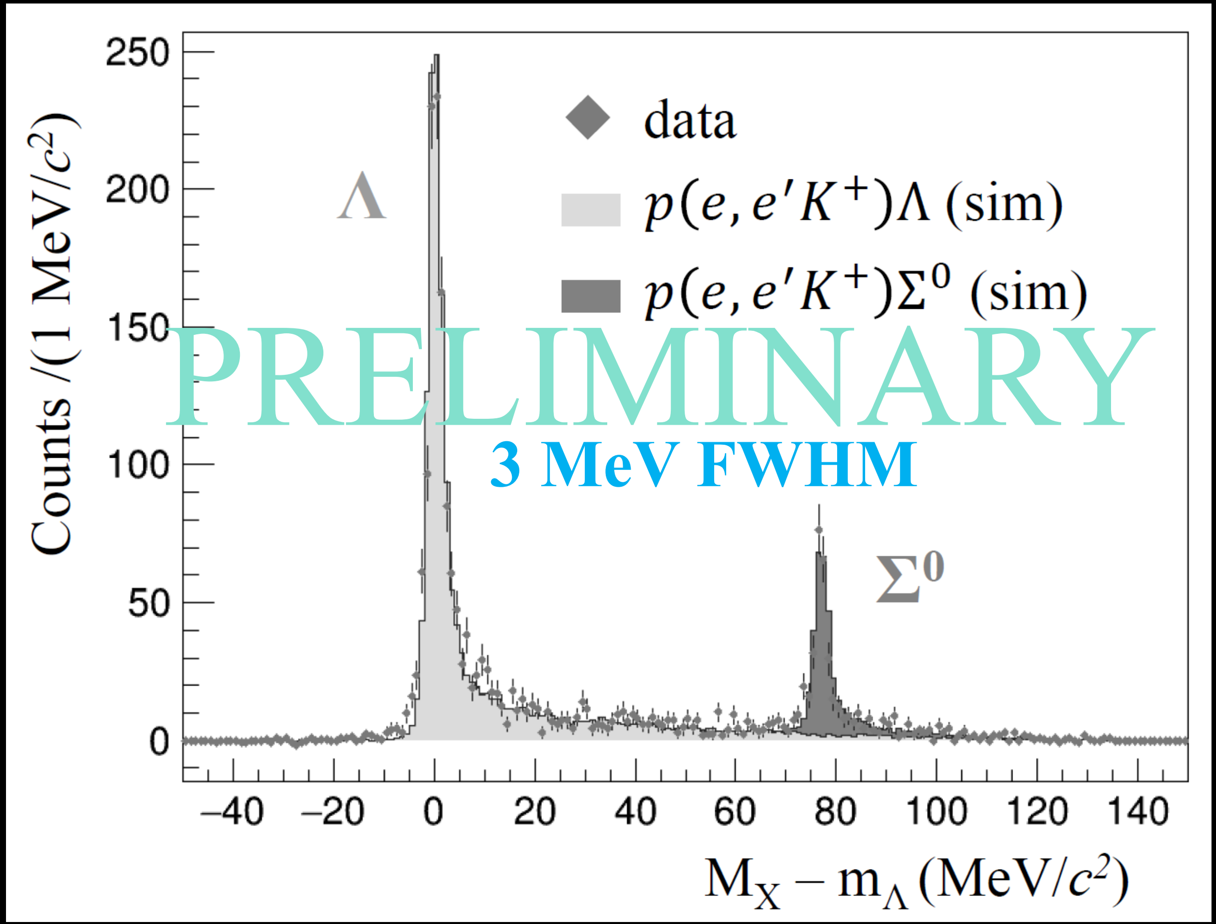
Timing consistency between L and R assuming m_K → Coin time (ns)

Energy calibration by Λ and Σ

Inside of scattering chamber



$H(e,e'K^+)\Lambda, \Sigma^0$

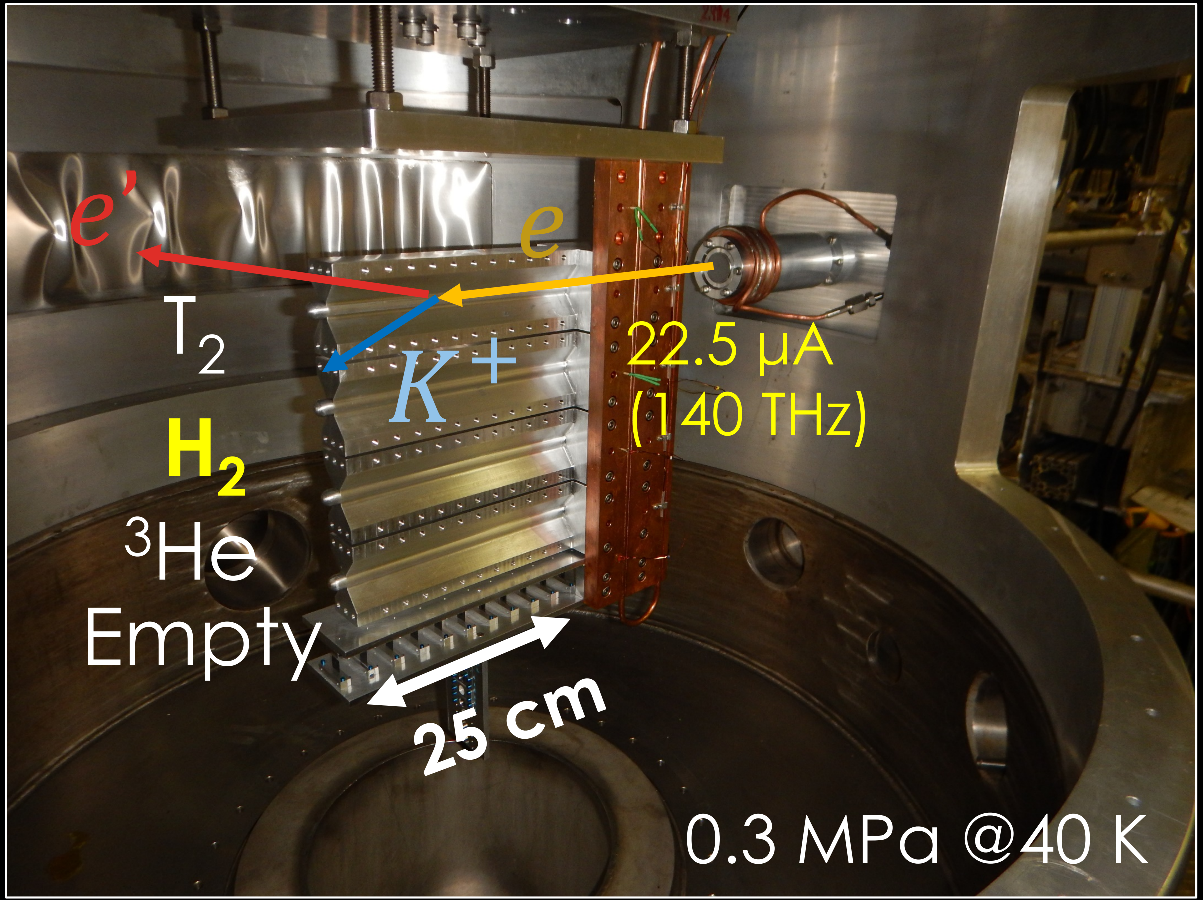


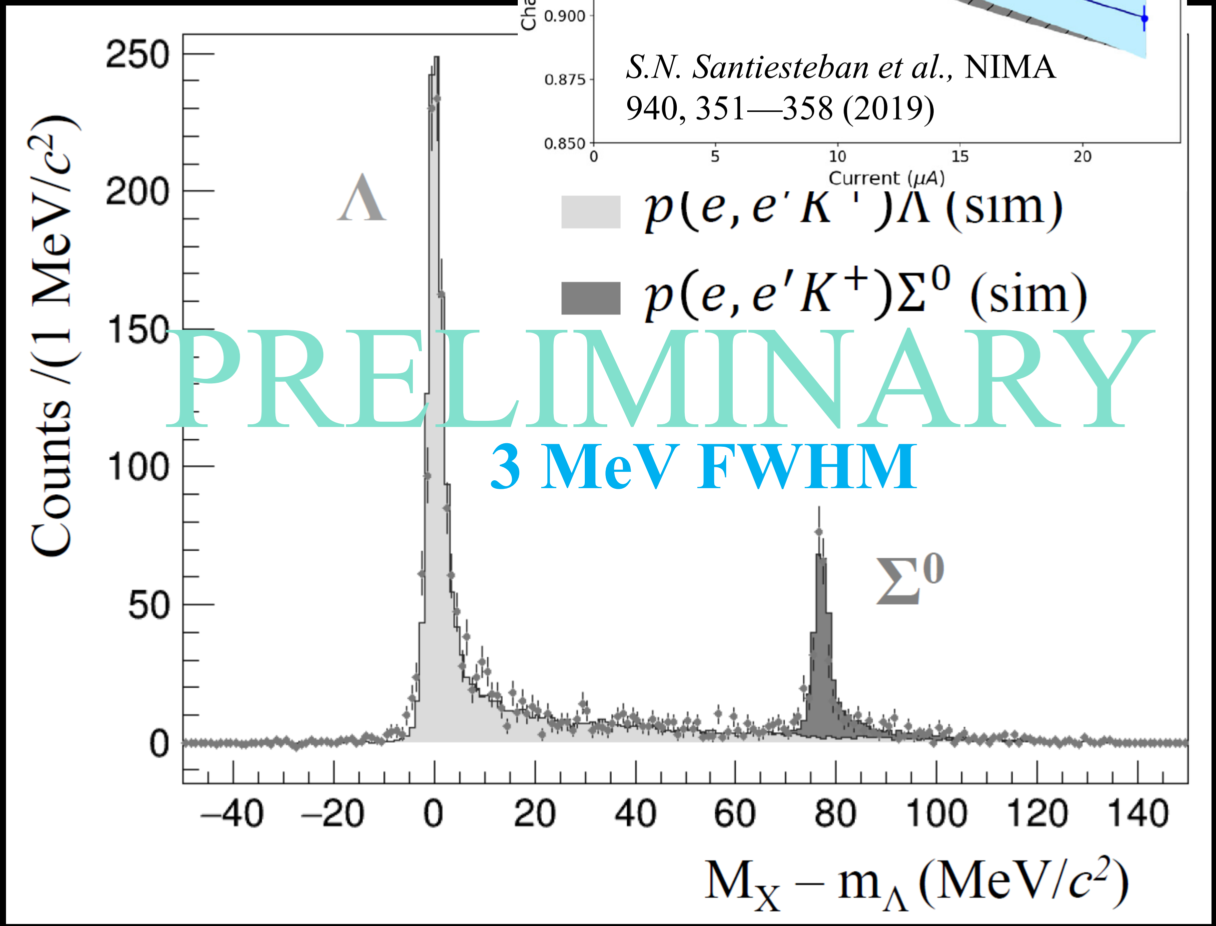
➡ System worked as we designed

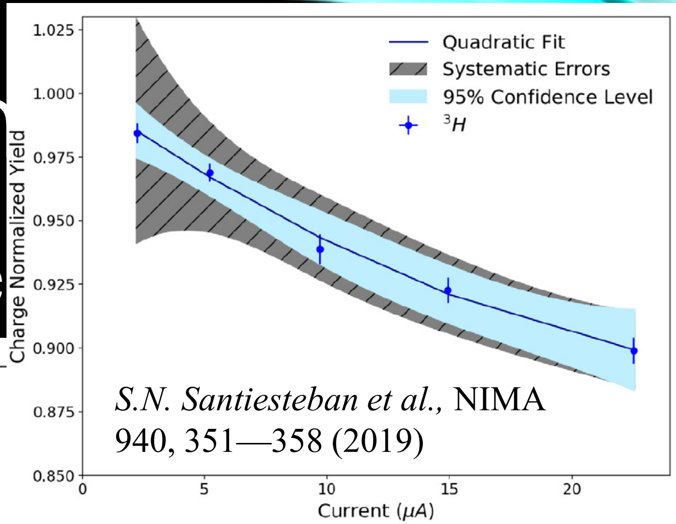
Energy calibration

H(e,e

Inside of scattering chamber







S.N. Santiesteban et al., NIMA 940, 351—358 (2019)

➡ System worked as we designed

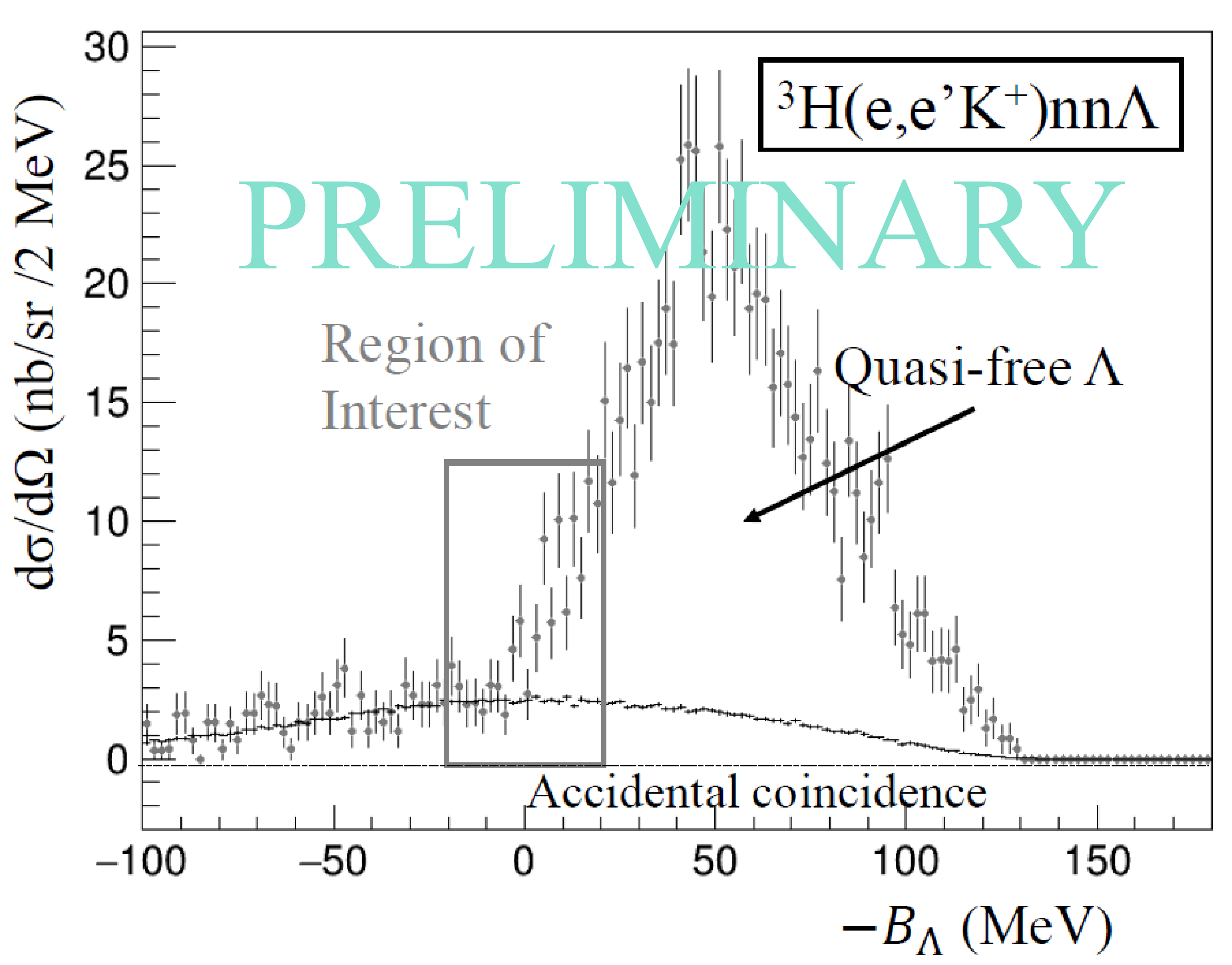
CROSS SECTION ANALYSIS

1. Acceptance cut
   → Lower statistics
2. Systematic error in addition to statistical error

Other ongoing analyses:

- A) Peak search with higher statistics
- B) Λn FSI fom QF shape

Theoretical calculations are needed !



FIT RESULT (PRELIMINARY)

Test case1: narrow width Γ = 0.8 MeV
K.M.Kamada et al.,
EPJ Conf. 113, 07004 (2016)

Test case2: wide width Γ = 4.7 MeV
V.B. Belyaev et al., NPA 803, 210 (2008)

Unbinned maximum likelihood fitting
→ Cross section

Narrow width

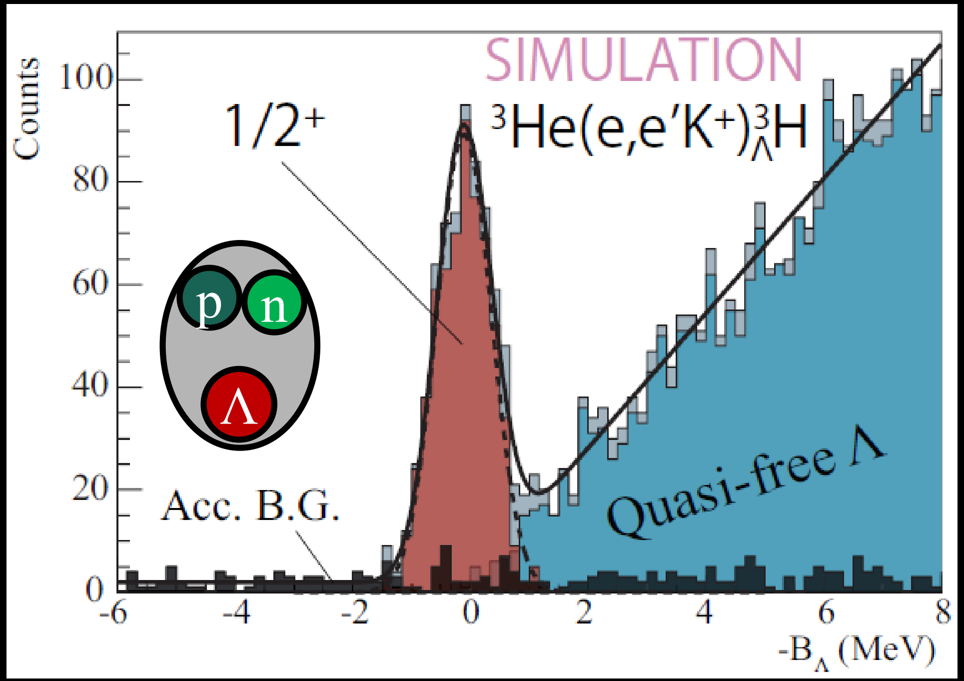
Wide width

dσ/dΩ (nb/sr)

dσ/dΩ (nb/sr)

PRELIMINARY

Future programs being prepared



- $^{3,4}_{\Lambda}H$ (E12-19-002) → lifetime puzzle, CSB, $3/2^+$
- $^{40,48}_{\Lambda}K$ (E12-15-008) → Isospin dependence
- $^{208}_{\Lambda}Tl$ (E12-20-013) → NNΛ interaction

Very high accuracy

$$\Delta B^{total}_{\Lambda} = \pm 60\ \mathrm{keV}$$

➡ Aim to carry out in 2023 or 2024

SUMMARY

1. **Hypernuclear study by (e,e'K$^+$)**
   - **High resolution (0.5—1 MeV FWHM) / High accuracy**
2. **Project introduced**
   - Test of the charge symmetry breaking for p-shell hypernuclei → Small
   - $nn\Lambda$ **search** (2018) → in analysis
   - Future projects (2023, 24〜)
     - ${}^{3,4}_{\Lambda}\mathrm{H}$ (E12-19-002) → lifetime puzzle / 3/2$^+$ existence for hypertriton, CSB
     - ${}^{40,48}_{\Lambda}\mathrm{K}$ (E12-15-008) → Isospin dependence
     - ${}^{208}_{\Lambda}\mathrm{Tl}$ (E12-20-013) → NNΛ interaction

ΛNN interaction

THANK YOU FOR YOUR ATTENTION